Effect of heavy-quark energy loss on the muon differential production cross section in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV

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Abstract

We study the nuclear modification factors R_{AA} and R_{CP} of the high transverse momentum ($5 < p_{\mathrm{t}} < 60$ GeV/c) distribution of muons in Pb–Pb collisions at LHC energies. We consider two pseudo-rapidity ranges covered by the LHC experiments: $|\eta| < 2.5$ and $2.5 < \eta < 4$. Muons from semi-leptonic decays of heavy quarks (c and b) and from leptonic decays of weak gauge bosons (W and Z) are the main contributions to the muon p_{t} distribution above a few GeV/c. We compute the heavy quark contributions using available pQCD-based programs. We include the nuclear shadowing modification of the parton distribution functions and the in-medium radiative energy loss for heavy quarks, using the mass-dependent BDMPS quenching weights. Muons from W and Z leptonic decays, that dominate the yield at high p_{t}, can be used as a medium-blind reference to observe the medium-induced suppression of beauty quarks.

Key words: Quark Gluon Plasma, Relativistic Heavy Ion Collisions, Heavy Quarks, Weak Gauge Bosons, Muons
PACS: 24.85.+p, 25.75.Dw, 25.75.-q

1 Introduction

Heavy quarks are regarded as effective probes of the strongly-interacting medium produced in ultra-relativistic heavy-ion collisions, since they are produced in

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the initial hard-scattering processes and they may subsequently interact with the medium itself. At the Relativistic Heavy Ion Collider (RHIC), a significant suppression of the so called 'non-photonic electrons', expected to be produced in the semi-leptonic decay of charm and beauty hadrons, has been measured in central Au–Au collisions at centre-of-mass energy $\sqrt{s_{\rm NN}} = 200$ GeV per nucleon–nucleon collision, indicating a substantial energy loss of heavy quarks in a strongly-interacting medium [1,2].

In Pb–Pb collisions at the Large Hadron Collider (LHC), the energy per nucleon–nucleon collision will be of 5.5 TeV, about 30 times larger than at RHIC, opening up a new era for the study of strongly-interacting matter at high energy density ('QCD medium'). Heavy-quark medium-induced energy loss will be one of the most captivating topics to be addressed in this novel energy domain [3]. In hadron–hadron collisions at LHC energies, muons are predominantly produced in semi-leptonic decays of heavy-flavoured hadrons —mostly beauty for muon $p_{\rm t} \gtrsim 4$ GeV/c. Thus, in heavy-ion collisions, the muon $p_{\rm t}$ distribution is sensitive to b-quark energy loss effects. In absence of nuclear effects, the initial heavy-quark production yields are expected to scale from proton–proton (pp) to nucleus–nucleus collisions in a given centrality class, according to the average number $\langle N_{\rm coll}\rangle$ of inelastic nucleon–nucleon collisions (binary scaling). Under this assumption, the in-medium energy loss of heavy quarks would induce a suppression of the high-$p_{\rm t}$ muon yield with respect to the binary-scaled yield measured in pp collisions. The suppression can be quantified as a reduction with respect to unity of the nuclear modification factor:

$$R_{\rm AA}(p_{\rm t}, \eta) = \frac{1}{\langle N_{\rm coll}\rangle} \frac{{\rm d}^2 N_{\rm AA}/{\rm d}p_{\rm t}{\rm d}\eta}{{\rm d}^2 N_{\rm pp}/{\rm d}p_{\rm t}{\rm d}\eta}\,. \tag{1}$$

However, initial-state effects, like for example nuclear shadowing of the parton distribution functions, could significantly reduce the initial production yields in nucleus–nucleus collisions, thus making more difficult to relate a reduction of $R_{\rm AA}$ to b-quark energy loss. At the LHC, muons from W and Z decays can provide an intrinsic calibration for the muon nuclear modification factor and a test of the binary scaling assumption. Due to the large amount of energy available at the LHC, W and Z bosons will be produced with significant cross sections in the hard parton–parton scatterings, and their initial yields are expected to scale with $\langle N_{\rm coll}\rangle$. As we will show, the muons from the decays $\rm W \to \mu\nu_\mu$ and $\rm Z \to \mu\mu$ are predicted to dominate the muon $p_{\rm t}$ distribution for $p_{\rm t} \gtrsim 30$ GeV/c.

Three experiments, ALICE [4,5], ATLAS [6], and CMS [7], will measure the production of muons in heavy-ion collisions, covering different acceptance regions. The ALICE Muon Spectrometer covers the pseudo-rapidity range $2.5 < \eta < 4$ for $p > 4$ GeV/c ($p_{\rm t} \gtrsim 1$ GeV/c) . ATLAS and CMS can measure

muons at central pseudo-rapidity, $|\eta| \lesssim 2.5$, with a larger cutoff, $p_t > 3$–4 GeV/c. As we will quantify in section 4, the high-p_t reach for the measurement of the inclusive muon production spectrum is expected to extend well into the region where muons from W and Z decays become dominant over muons from beauty decays.

In this work, we study the effect of heavy-quark energy loss on the transverse momentum distribution of muons in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV within the acceptance of the LHC experiments. The weak gauge bosons contributions (section 2.1) to the muon p_t and rapidity distributions are obtained from the PYTHIA [8] event generator, taking into account the isospin content of the colliding nuclei and normalizing the cross section to the values predicted by the calculations in Refs. [9,10]. The heavy quark contributions (section 2.2) to the muon p_t distribution are obtained from a NLO perturbative QCD(pQCD) calculation (MNR [11]) supplemented with the mass-dependent BDMPS quenching weights for radiative energy loss [12], quark fragmentation *à la* Peterson [13] and semi-muonic decay with the spectator model [14]. In the calculation of heavy-quark energy loss the decreased medium density at large rapidities is taken into account by assuming the BDMPS transport coefficient $\hat{q}$ to scale as $\hat{q}(\eta) \propto {\rm d}N_{\rm ch}/{\rm d}\eta$ (section 3). In section 4 we present and discuss the resulting muon p_t distribution in the 10% most central Pb–Pb collisions, the Pb–Pb-to-pp nuclear modification factor $R_{\rm AA}(p_t)$ and the central-to-peripheral nuclear modification factor $R_{\rm CP}(p_t)$, without and with the inclusion of heavy-quark energy loss.

2 Muon p_t distribution in hadron–hadron collisions

The muon p_t distributions in pp and Pb–Pb collisions at LHC energies are calculated considering the semi-muonic decays of heavy-flavoured hadrons and the muonic decay of W and Z bosons. The procedure used to evaluate the production differential cross section per nucleon–nucleon collision is described in the following.

2.1 W *and* Z *decay muons*

At the LHC, the c.m.s. energy is large enough to allow the production of massive particles such as the W and Z bosons. The p_t and rapidity distributions of W/Z and of their decay muons are obtained from the PYTHIA event generator [8], that reproduces the measured p_t distributions in $\rm p\overline{p}$ collisions at the Tevatron ($\sqrt{s} = 1.8$ TeV) [15,16]. Since in hadron–hadron collisions, at leading order, W and Z bosons are produced by quark–anti-quark annihilation,

there could be a dependence of their production cross section on the isospin of the input channel. In nucleus–nucleus collisions this dependence can be mimicked by a weighted cocktail of proton–proton (pp), neutron–neutron (nn), proton–neutron (pn) and neutron–proton (np) collisions. The cross section per nucleon–nucleon binary collision can be expressed as

$$\frac{\mathrm{d}^2\sigma_{\mathrm{NN}}}{\mathrm{d}p_{\mathrm{t}}\mathrm{d}y} \approx \frac{Z^2}{A^2} \times \frac{\mathrm{d}^2\sigma_{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{t}}\mathrm{d}y} + \frac{(A-Z)^2}{A^2} \times \frac{\mathrm{d}^2\sigma_{\mathrm{nn}}}{\mathrm{d}p_{\mathrm{t}}\mathrm{d}y} + \frac{Z\cdot(A-Z)}{A^2} \times \left\{ \frac{\mathrm{d}^2\sigma_{\mathrm{pn}}}{\mathrm{d}p_{\mathrm{t}}\mathrm{d}y} + \frac{\mathrm{d}^2\sigma_{\mathrm{np}}}{\mathrm{d}p_{\mathrm{t}}\mathrm{d}y} \right\}, \tag{2}$$

where A and Z are the mass number and the atomic number of the colliding nuclei. CTEQ 4L [17] parton distributions functions (PDFs) are used, and nuclear shadowing is accounted for via the EKS98 parametrization [18]. The resulting p_{t} distributions are normalized to the cross sections obtained from Refs. [9,10], that is a cross section per nucleon–nucleon collision of 6.56 (7.34) nb for the W and 0.63 (0.68) nb for the Z in Pb–Pb (pp) collisions at 5.5 TeV, including the muonic branching ratios (10.6% for W and 3.4% for Z [19]). Notice that the Z production cross section is about ten times smaller than that of the W [20,21]. The uncertainty due to neglecting higher order corrections (next-to-next-to-leading order) was quantified as 1–2% in Ref. [9] by varying the values of the factorization and renormalization scales. The uncertainty due to the errors on the PDFs was quantified as about 10% in Ref. [22].

2.2 Heavy-quark decay muons

Within the pQCD collinear factorization framework, the expression for the production cross section of heavy-flavoured hadrons in the collision of two hadrons A and B can be schematically written as:

$$\frac{\mathrm{d}^2\sigma^{AB\to h}_{\text{no medium}}}{\mathrm{d}p_{\mathrm{t}}\mathrm{d}y} = \sum_{i,j} \int \mathrm{d}x_{i/A}\,\mathrm{d}x_{j/B}\; f_{i/A}(x_{i/A})\; f_{j/B}(x_{j/B}) \times \frac{\mathrm{d}^2\hat{\sigma}^{ij\to \mathrm{Q}\overline{\mathrm{Q}}X}}{\mathrm{d}p_{\mathrm{t,Q}}\mathrm{d}y_{\mathrm{Q}}} \times \frac{D_{h/\mathrm{Q}}(z)}{z^2}, \tag{3}$$

where $f_{i/A}(x_{i/A})$ and $f_{j/B}(x_{j/B})$ are the parton distribution functions, the differential probabilities for the partons i and j to carry momentum fractions $x_{i/A}$ and $x_{j/B}$ of their respective nucleons. $\hat{\sigma}^{ij}$ is the cross section of the partonic process $ij \to \mathrm{Q}\overline{\mathrm{Q}}X$. The fragmentation function $D_{h/\mathrm{Q}}(z)$ is the probability for the heavy quark Q to fragment into a hadron h with transverse momentum $p_{\mathrm{t}} = z\,p_{\mathrm{t,Q}}$. To simplify the notation, we have dropped the $\sqrt{s}$ dependence of

$\hat{\sigma}^{ij}$ and the renormalization/factorization scale dependences of $f_{i/A(j/B)}$, $\hat{\sigma}^{ij}$ and $D_{h/\mathrm{Q}}$ (the squares of scales are normally of the order of the momentum transfer $Q^2 \sim p_{\mathrm{t,Q}}^2$ of the hard scattering).

We use the NLO pQCD calculation implemented in the HVQMNR program [11] to obtain the heavy-quark p_{t}–y double-differential cross sections, with the following parameters values: for charm, $m_{\mathrm{c}} = 1.2~\mathrm{GeV}/c^2$ and factorization and renormalization scales $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = 2\mu_0$, where $\mu_0 \equiv \sqrt{m_{\mathrm{Q}}^2 + (p_{\mathrm{t,Q}}^2 + p_{\mathrm{t,\overline{Q}}}^2)/2}$; for beauty, $m_{\mathrm{b}} = 4.75~\mathrm{GeV}/c^2$ and $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \mu_0$. CTEQ 4M [17] parton distribution functions are used, and nuclear shadowing is taken into account with the EKS98 parametrization [18]. For the b quark, the perturbative uncertainty was quantified, by varying the scales, in about 30% for $p_{\mathrm{t}} > 30$ GeV/c [23]. Starting from the heavy-quark double-differential cross sections at NLO, we obtain the muon-level cross sections using the following Monte Carlo procedure. We sample p_{t} and y of a c (or b) quark according to the shape of the NLO cross section and fragment it to a hadron using the Peterson [13] fragmentation function following the parameterization obtained in a recent analysis of $\mathrm{e}^+\mathrm{e}^-$ data from LEP [23]. Finally, we decay the hadron into a muon according to the spectator model [24]. In the spectator model, the heavy quark in a meson is considered to be independent of the light quark and is decayed as a free particle according to the $V - A$ weak interaction [14]. Thus, we assume the momentum of the hadron to be entirely carried by the constituent heavy quark and we perform the heavy-quark three-body decay, $\mathrm{c} \to \mathrm{s}\mu\nu_\mu$ or $\mathrm{b} \to \mathrm{c}\mu\nu_\mu$, to obtain the muon transverse momentum and rapidity. The muon production cross sections per nucleon–nucleon collision from charm (beauty) at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV that we obtain are 0.415 mb (20 μb) in Pb–Pb collisions and 0.637 mb (23 μb) in pp collisions. A charm (beauty) semi-muonic branching ratio of 9.6% (11.0%) [19] has been considered. We do not include the muons from the cascade decay $\mathrm{b} \to \mathrm{c} \to \mu$, because their yield is expected to become negligible with respect to that of the direct muons from b, for p_{t} larger than a few GeV/c [25]. The uncertainty on the beauty component, which dominates the heavy-flavour muon yields in the p_{t} range relevant to our study, can be quantified as about 30%, on the basis of a recent analysis [23] that considered the perturbative uncertainty (variation of the factorization and renormalization scales), the uncertainty on the PDFs and the uncertainty on the fragmentation.

3 Heavy-quark energy loss

Now we will compute the muon p_{t} distribution taking into account the heavy-quark energy loss in the strongly-interacting medium that is expected to be formed in central Pb–Pb collisions at LHC energies. For modelling the energy

loss of heavy quarks by medium-induced gluon radiation, we used the quenching weights in the multiple soft scattering approximation, which were derived in Ref. [12] in the framework of the BDMPS formalism [26]. Schematically, energy loss is introduced by modifying Eq. (3) to:

$$\frac{\mathrm{d}^2\sigma^{AB\to h}_{\mathrm{medium}}}{\mathrm{d}p_\mathrm{t}\mathrm{d}y} = \sum_{i,j}\int \mathrm{d}x_{i/A}\ \mathrm{d}x_{j/B}\ \mathrm{d}\Delta E \times f_{i/A}(x_{i/A})\ f_{j/B}(x_{j/B}) \times \\ \frac{\mathrm{d}^2\hat{\sigma}^{ij\to \mathrm{Q}\overline{\mathrm{Q}}X}(p_{\mathrm{t,Q}}+\Delta E)}{\mathrm{d}p_{\mathrm{t,Q}}\mathrm{d}y_\mathrm{Q}} \times P(\Delta E, \hat{q}, L, m_\mathrm{Q}/E) \times \frac{D_{h/\mathrm{Q}}(z)}{z^2}, \quad (4)$$

where E is the heavy-quark energy and ΔE is the radiated energy. The quenching weight, represented by $P(\Delta E, \hat{q}, L, m_\mathrm{Q}/E)$, is the probability for a heavy quark with mass m_Q and energy E to lose an energy ΔE while propagating over a path length L inside a medium with transport coefficient $\hat{q}$. The latter is defined as $\langle k_\mathrm{t}^2\rangle/\lambda$, the average transverse momentum, k_t, squared transferred from the medium to the parton per unit mean free path λ. It is expected to be proportional to the volume density $\mathrm{d}N^\mathrm{g}/\mathrm{d}V$ of gluons in the medium (thus, to its energy density) and to the typical momentum transfer per scattering.

We calculate the energy loss ΔE following the Monte Carlo approach introduced in Ref. [27] for light quarks and gluons, and adapted for heavy quarks in Refs. [12,28]. We start by sampling the heavy-quark kinematics, p_t and y, according to the NLO double-differential cross section. Then, we sample the parton production point in the transverse plane (x,y) according to the Glauber-model [29] density $\rho_{\mathrm{coll}}(\mathrm{x},\mathrm{y})$ of binary collisions, and we sample the azimuthal parton propagation direction. We calculate the path length L and the value of $\hat{q}$, which is a mean value of the local time-averaged $(\overline{\ })$ transport coefficient $\overline{\hat{q}}(\mathrm{x},\mathrm{y})$ along the path of the parton. We do not include the expansion of the medium in the longitudinal and transverse directions. However, it has been shown in Ref. [30] that, numerically, the effects of a time-dependent medium on parton energy loss can be accounted for by an equivalent static medium, specified in terms of the time-averaged transport coefficient $\overline{\hat{q}}$. This is confirmed by recent works (see e.g. Ref. [31]), showing that the inclusion of the medium evolution by a full hydrodynamical simulation does not significantly change or improve, with respect to the assumption of a static medium, the results for the suppression of the high-p_t R_{AA} in central Au–Au collisions at RHIC. We assume that our approach for the estimation of L is valid for rapidities belonging to the "central plateau" of the charged particle distribution [32], which is expected to be as large as $|y| < 4.5$ at LHC energies [3]. We now sample a ΔE value, according to the quenching weight P, and we modify the quark kinematics to $(p'_\mathrm{t} = p_\mathrm{t} - \Delta E,\ y' = y)$. As in Ref. [12], heavy quarks that lose all their energy $(\Delta E > p_\mathrm{t})$ are redistributed according to the thermal distribution $\mathrm{d}N/\mathrm{d}m_\mathrm{t} \propto m_\mathrm{t}\exp(-m_\mathrm{t}/T)$ with $T = 0.3$ GeV. The muons from the decay of these thermalized quarks populate the region $p_\mathrm{t} \lesssim 2$ GeV/c, out-

side the range of interest for the present study. We assume the heavy-quark rapidity to stay constant during the process of energy loss, since heavy quarks co-move with the longitudinally-expanding medium and any modification of the initial heavy-quark rapidity should remain small. Finally, we apply fragmentation and decay as described in section 2.2.

In Ref. [27] the local $\hat{q}$ transverse profile at central rapidity ($y = 0$) is assumed to be proportional to the density of binary collisions. Since we want to study muon production in a broad rapidity range ($|y| \lesssim 4$), we introduce a dependence of the local $\hat{q}$ on the pseudo-rapidity η in order to account for the reduced medium density in the forward direction. Namely, we assume the transport coefficient $\hat{q}$ to scale as a function of pseudo-rapidity according to the gluon pseudo-rapidity density of the medium $\mathrm{d}N^{\mathrm{g}}/\mathrm{d}\eta$, this choice being justified by the fact that $\mathrm{d}N^{\mathrm{g}}/\mathrm{d}V$ scales in η according to $\mathrm{d}N^{\mathrm{g}}/\mathrm{d}\eta$. We assume the pseudo-rapidity density of charged particles and the pseudo-rapidity density of gluons to have the same dependence on η and we write [33]:

$$\overline{\hat{q}}(\mathrm{x},\mathrm{y},\eta) = \kappa \cdot \rho_{\mathrm{coll}}(\mathrm{x},\mathrm{y}) \cdot \left[\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}(\eta) \bigg/ \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}(0) \right], \tag{5}$$

where κ is a constant that sets the scale of $\hat{q}$. We use two values of κ that were estimated for central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV by scaling the values extracted from an analysis of the light-flavour hadrons suppression at RHIC [27,34]. The corresponding values for the parton-averaged ($\langle\ \rangle$) and time-averaged ($\overline{\ }$) transport coefficient [1] are $\left\langle \overline{\hat{q}} \right\rangle = 25$ and $100\ \mathrm{GeV}^2/\mathrm{fm}$. For the pseudo-rapidity dependence we use the pseudo-rapidity distribution of charged particles predicted for Pb–Pb collisions at the LHC in Ref. [35]. The effect of this dependence on the suppression of muons from heavy-quark decays is expected to be small, because $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ is predicted to have only a modest variation in the range $|\eta| < 4$ (for illustration, for $\eta = 3$ it would be reduced by about 15% with respect to $\eta = 0$).

Before presenting our results, we point out that, in addition to radiative energy loss, there are other possible medium-induced effects (e.g.: collisional energy loss of heavy quarks [36], in-medium hadronization and dissociation of heavy-flavour hadrons [37], formation of bound states and hadronization of heavy quarks via coalescence [38]) that could noticeably affect the muon spectrum for $p_{\mathrm{t}} \lesssim 10$ GeV/c. These effects have not been considered in the present study. And one has to keep in mind that all current jet quenching models do not describe the suppression of single non-photonic electron p_{t} spectra at RHIC equally well as they do describe the suppression of pion spectra. It is with this caveat that one should view the predictions for LHC based on these models.

[1] Hereafter indicated as $\hat{q}$, for simplicity.

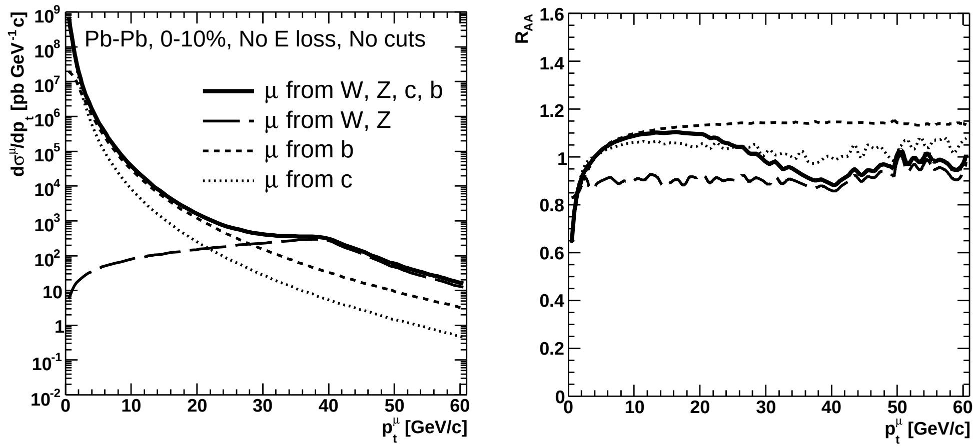

Fig. 1. Muons in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV. Heavy-quark energy loss is not included and no acceptance cuts are applied. Left-hand panel: $p_{\rm t}$-differential cross section normalized to one binary nucleon–nucleon collision. Right-hand panel: nuclear modification factor $R_{\rm AA}$ with respect to pp collisions.

4 Results and discussion

We start by presenting, in the left-hand panel of Fig. 1, the muon production cross-section as a function of transverse momentum in the 10% most central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV, when only nuclear shadowing is included. The contributions from charm, beauty and weak gauge bosons are shown separately. Muons from charged pion and kaon decays and from Drell-Yan processes ($q\overline{q} \rightarrow \mu^+\mu^-$) are ignored here, because both are expected to be negligible in the transverse momentum range $5 \lesssim p_{\rm t} \lesssim 60$ GeV/c [4,7]. Due to their large masses, W and Z bosons are mainly produced with small transverse momentum, $p_{\rm t} \ll m_{\rm W,Z}$. Therefore, the decay muons have typically $p_{\rm t} \sim m_{\rm W,Z}/2$. The latest qualitatively explains the shape of the $p_{\rm t}$ distribution of muons from the decay of the W and Z, which "peaks" at $p_{\rm t} \approx 40$ GeV/c. Among the contributions that we compute, muons from charm decays are predominant in the low-$p_{\rm t}$ range, 2–4 GeV/c. In the range 4–30 GeV/c beauty decays prevail, and at larger $p_{\rm t}$ the W decays represent the largest contribution to the muon spectra. We may note that these values for the "crossing points" in $p_{\rm t}$ are somewhat dependent on the perturbative uncertainties of NLO calculations (choice of the fragmentation and renormalization scales) and on other systematics in the fragmentation and decay kinematics. For example, a variation of $\pm 30\%$ of yield of the beauty component (see section 2.2) implies a shift of the crossing point by approximately ± 2 GeV/c. As discussed in Refs. [20,21], the experimental measurement of the ratio of positive-to-negative muons could help to determine these crossing points. For illustration of the expected significance for high-$p_{\rm t}$ muons, we quote the production yield of muons from W

decay in minimum-bias Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV for an integrated luminosity of 5×10^{32} cm^{-2} (the expected integrated luminosity to be collected by each of the three experiments within one month of data-taking). In this case, about 7.5×10^4 muons from W decays will be produced in the range $30 < p_{\rm t} < 50$ GeV/c. Out of them, about 6.0×10^4 will be produced in $|\eta| < 2.5$ and 0.7×10^4 in $2.5 < \eta < 4.0$.

In view of exploring the final-state effects (heavy-quark energy loss) on the muon spectrum, we first focus on the influence of the initial-state effects, i.e. nuclear shadowing, by analysing the nuclear modification factor $R_{\rm AA}$ as a function of transverse momentum (right-hand panel of Fig. 1). The short-dashed and dotted lines represent the heavy-quark decays contributions; at low $p_{\rm t}$ (2–4 GeV/c) they probe the small x range of the gluon PDF $g(x)$, where, according to the EKS98 parametrization [18], we have shadowing: the PDF in the Pb nucleus is suppressed with respect to the PDF in the free proton ($C_{\rm shad}(x, Q^2) = g^{\rm Pb}(x, Q^2)/g^{\rm p}(x, Q^2) < 1$). Thus, $R_{\rm AA} < 1$. For larger muon $p_{\rm t}$ ($\gtrsim 10$ GeV/c) a higher x range is probed, and we begin to explore the anti-shadowing region ($C_{\rm shad} > 1$), so $R_{\rm AA} > 1$ as is observed in Fig. 1. For illustration, in table 1 we report a qualitative estimation of the probed (x_1, x_2) values and of the corresponding EKS98 shadowing factors $C_{\rm shad} = C_{\rm shad}(x_1, Q^2) \times C_{\rm shad}(x_2, Q^2)$ for heavy quarks and W/Z bosons in Pb–Pb collisions at 5.5 TeV, as a function of the decay-muon rapidity and transverse momentum ($\overline{C_{\rm shad}}$ is the mean value of $C_{\rm shad}$). The x values were obtained using the PYTHIA event generator for the leading order processes $\rm gg \to Q\overline{Q}$ and $\rm q\overline{q} \to W/Z$. For these two processes, we have, qualitatively, $s_{\rm NN}x_1x_2 = Q^2 \approx 4\,(p_{{\rm t},\mu}^2 + m_{\rm Q}^2)$ and $s_{\rm NN}x_1x_2 = Q^2 \approx m_{\rm W\,(Z)}^2 \approx 4\,p_{{\rm t},\mu}^2$, respectively; and, for both, $x_1 \approx 2\,p_{{\rm t},\mu}\exp(+y_\mu)/\sqrt{s_{\rm NN}}$, $x_2 \approx 2\,p_{{\rm t},\mu}\exp(-y_\mu)/\sqrt{s_{\rm NN}}$. Weak gauge boson decays (long-dashed line in Fig. 1) probe the quarks nuclear shadowing, which fluctuates around its mean value of 0.9. The overall nuclear modification factor of muons (solid line in Fig. 1) increases rapidly with $p_{\rm t}$ up to a value of about 1.1 and then decreases to about 0.9. In order to explore the uncertainties due to the limited knowledge of the nuclear PDFs in the kinematic region relevant to our study, we considered two other parametrizations of the nuclear parton distribution: nDS [39] and HKN07 [40]. The values of the corresponding shadowing factors are reported in table 1. We note that the shadowing factor uncertainty for heavy quarks at high $p_{\rm t}$ is 7% and for weak gauge boson is less than 5%. For heavy quarks at low $p_{\rm t}$, it becomes as large as 20% for charm and 10% for beauty. Note that the study of proton–nucleus collisions at RHIC energies has been absolutely necessary to disentangle cold and hot nuclear matter effects. Cold nuclear matter effects at LHC energies remain relatively unknown. Therefore, p–Pb runs at the LHC will be needed in order to fully understand the nuclear modification factors measured in Pb–Pb.

We now include in the calculation the in-medium energy loss for heavy quarks. We start by considering the nuclear modification factor $R_{\rm AA}(p_{\rm t})$ of muons

Table 1
Qualitative estimation of Bjorken-x values and shadowing factors (according to EKS98 [18], nDS(NLO) [39] and HKN07(NLO) [40]) for heavy quarks and W/Z bosons produced in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV as a function of the decay-muon y and $p_{\rm t}$ (in GeV/c). Details in the text.

	y	$p_{\rm t}$	x_1	x_2	$C^{EKS}_{\rm shad}$	$\overline{C^{EKS}_{\rm shad}}$	$C^{nDS}_{\rm shad}$	$\overline{C^{nDS}_{\rm shad}}$	$C^{HKN}_{\rm shad}$	$\overline{C^{HKN}_{\rm shad}}$
c	0	0	$4 \cdot 10^{-4}$		0.50	0.65	0.81	0.92	0.74	0.87
	0	30	$1 \cdot 10^{-2}$		1.10		1.09		0.93	
	3	0	$9 \cdot 10^{-3}$	$2 \cdot 10^{-5}$	0.57		0.83		0.74	
	3	30	$2 \cdot 10^{-1}$	$5 \cdot 10^{-4}$	0.91		0.96		1.09	
b	0	0	$2 \cdot 10^{-3}$		0.77	0.85	0.92	0.95	0.83	0.93
	0	30	$1 \cdot 10^{-2}$		1.10		1.00		0.93	
	3	0	$3 \cdot 10^{-2}$	$8 \cdot 10^{-5}$	0.85		0.93		0.85	
	3	30	$2 \cdot 10^{-1}$	$5 \cdot 10^{-4}$	0.91		0.96		1.09	
W	0	all	$1 \cdot 10^{-2}$		0.89	0.89	0.88	0.83	0.83	0.84
	3	all	$3 \cdot 10^{-1}$	$7 \cdot 10^{-4}$	0.76		0.77		0.85	
Z	0	all	$2 \cdot 10^{-2}$		0.90	0.93	0.89	0.83	0.84	0.83
	3	all	$3 \cdot 10^{-1}$	$8 \cdot 10^{-4}$	0.77		0.76		0.83	

from beauty decays in central (0–10%) Pb–Pb collisions, in order to study the effects of the b quark mass and of the dependence of the transport coefficient $\hat{q}$ on η according to $\mathrm{d}N_{\rm ch}/\mathrm{d}\eta$. The latter is relevant only in the large pseudo-rapidity range. The result is shown in Fig. 2. The shaded band represents our baseline result for the $\hat{q}$ range 25–100 GeV^2/fm, with mass effect ($m_{\rm b} = 4.75$ GeV) and with pseudorapidity dependence of $\hat{q}$. The suppression obtained at high $p_{\rm t}$, where $R_{\rm AA}$ becomes independent of $p_{\rm t}$, is about a factor 5 (10) for $\hat{q} = 25$ (100) GeV^2/fm. The suppression for electrons from beauty decays was calculated within the same framework (except for the treatment of hadronization and decay) in Ref. [12], for central rapidity and $p_{\rm t} \lesssim 15$ GeV/c. For the same $p_{\rm t}$ range, we obtain similar values for $R_{\rm AA}$. With reference to Fig. 2, by comparing the thick solid line ($m_{\rm b} = 4.75$ GeV) and the long-dash line ($m_{\rm b} = 0$), we notice that the quark mass effect in parton energy loss increases $R_{\rm AA}$ by up to a factor of three for $p_{\rm t} \sim 5$ GeV/c, and that some effect persists even at 15 GeV/c. When going to $p_{\rm t} \gtrsim 20$ GeV/c, the quark mass dependence becomes negligible since the quark mass becomes negligible with respect to the momentum. By comparing the thick and thin solid lines with $\hat{q} = 100$ GeV^2/fm, which are with and without η dependence of $\hat{q}$ respectively,

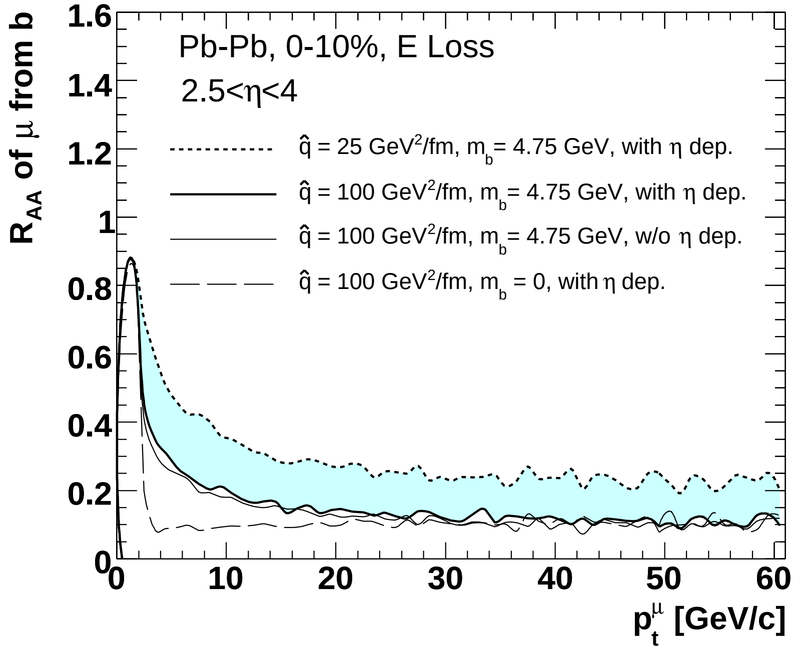

Fig. 2. Nuclear modification factor of muons from beauty decays with/without mass effect in the energy loss, and with/without pseudo-rapidity dependence of $\hat{q}$ ($\mathrm{d}N/\mathrm{d}\eta$ dependence), in the central (0–10%) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV in the pseudo-rapidity range $2.5 < \eta < 4.0$.

we conclude that this dependence has basically no effect on the amount of suppression in the range $2.5 < \eta < 4$.

Figure 3 shows the muon p_{t}-differential cross section and the nuclear modification factor for muons from W, Z, c and b decays in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV in the two pseudo-rapidity domains. The results with transport coefficient values $\hat{q} = 0$, 25 and 100 $\mathrm{GeV}^2/\mathrm{fm}$ are reported, where $\hat{q} = 0$ corresponds to the case of no energy loss. With reference to the upper panels of Fig 3, note that, since muons from W and Z decays are unaffected by the energy loss, the crossing point in transverse momentum of the distributions of b-quark and W-boson decay muons shifts down by ≈ 5 GeV/c at large rapidities and by ≈ 7 GeV/c at mid-rapidity, when energy loss is included. Concerning the muon $R_{\mathrm{AA}}(p_{\mathrm{t}})$ (lower panels of Fig. 3), at large pseudo-rapidities (on the left), with heavy-quark energy loss, the overall muon yield is suppressed by about a factor of 2–5 in the range $2 < p_{\mathrm{t}} < 20$ GeV/c, where the beauty contribution dominates. For higher p_{t}, R_{AA} increases rapidly in the $20 \lesssim p_{\mathrm{t}} \lesssim 30$ GeV/c range and flattens at around 0.8 above ≈ 30 GeV/c. The $\hat{q}$-independence of the R_{AA} of overall muons at large p_{t} is due to the fact that the W/Z boson contribution to the yield becomes dominant (see upper panels of Fig. 3). At mid-rapidity the behaviour is similar (lower-right panel). The small difference of the R_{AA} shape at different rapidities is due to the different proportion of heavy-quark and W/Z boson decays. For the same reason the

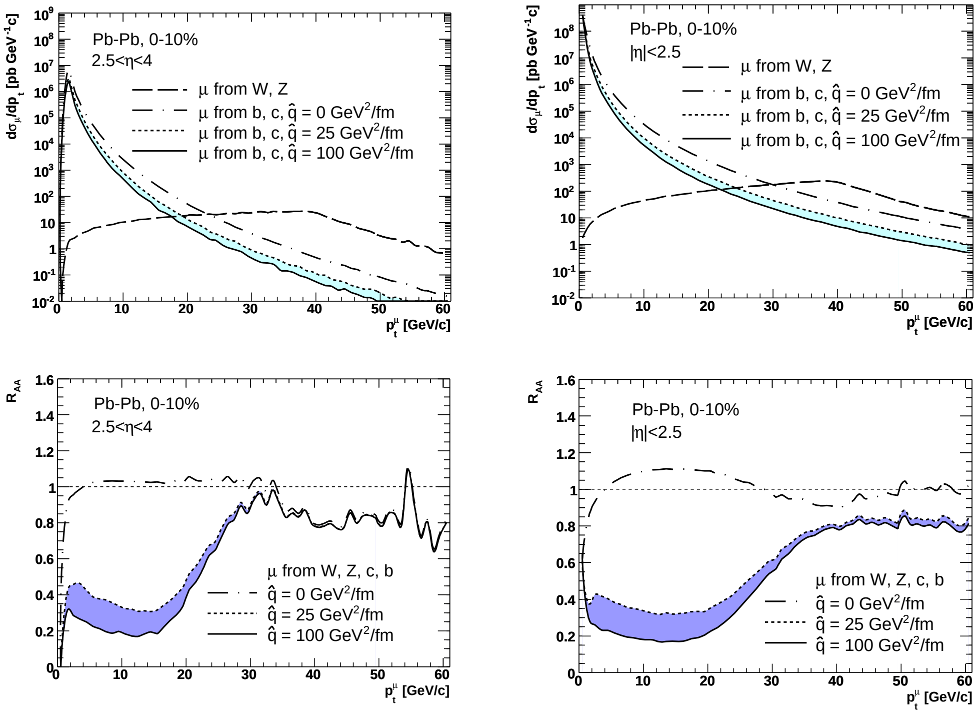

Fig. 3. Differential cross section per nucleon–nucleon collision and nuclear modification factor of muons from W, Z, c and b decays in central (0–10%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV. for $2.5 < \eta < 4$. The left-hand panel shows the results for $2.5 < \eta < 4$, the right-hand panel the results for $|\eta| < 2.5$.

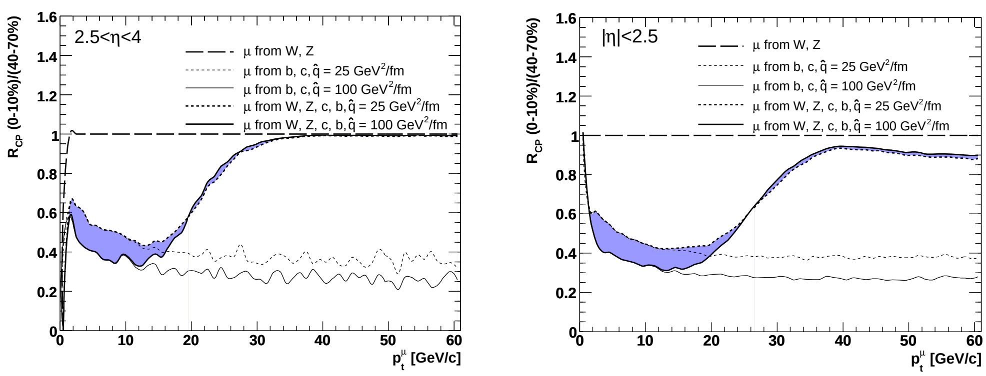

Fig. 4. Central (0–10%) to peripheral (40–70%) nuclear modification factors of muons from W, Z, c and b decays in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.5$ TeV. The left-hand panel shows the results for $2.5 < \eta < 4$, the right-hand panel the results for $|\eta| < 2.5$.

nuclear modification factor without energy loss (dot-dashed lines in the lower panels in Fig. 3) differs slightly from that obtained without acceptance cuts (solid line in Fig. 1).

Besides the Pb–Pb-to-pp nuclear modification factor $R_{\rm AA}$, also the central-

to-peripheral nuclear modification factor $R_{\rm CP}$ will provide information on the medium-induced suppression of b quarks. $R_{\rm CP}$ is defined as:

$$R_{\rm CP}(p_{\rm t}) = \frac{\langle N_{\rm coll}^{AA}\rangle^{\rm P}}{\langle N_{\rm coll}^{AA}\rangle^{\rm C}}\ \frac{{\rm d}^2N_{AA}^{\rm C}/{\rm d}p_{\rm t}{\rm d}y}{{\rm d}^2N_{AA}^{\rm P}/{\rm d}p_{\rm t}{\rm d}y}\,, \tag{6}$$

where the index C (P) stands for central (peripheral) collisions. From the experimental point of view, the $R_{\rm CP}$ measurement will be more straight-forward than the $R_{\rm AA}$ measurement, for the following two reasons. 1) The measurements in pp and in Pb–Pb will be affected by different systematic errors (especially for the cross section normalization), which will add up in the $R_{\rm AA}$ uncertainty. 2) pp collisions at the LHC will have different c.m.s. energy (14 TeV) with respect to Pb–Pb (5.5 TeV), therefore the muon spectra measured in pp will have to be extrapolated from 14 TeV to 5.5 TeV with the guidance of perturbative QCD calculations, introducing an additional systematic error of the order of 10% on $R_{\rm AA}$ [5].

In our calculation, the initial-state effects are assumed to be the same in central and peripheral collisions —namely, we do not include an impact parameter dependence for shadowing— thus, they cancel out in the central-to-peripheral ratio. As a consequence, the $R_{\rm CP}$ of muons from weak gauge boson decays is equal to one. The central (0–10%) to peripheral (40–70%) ratios are shown in Fig. 4. In central (0–10%) collisions the yield might be reduced with respect to peripheral collisions (40–70%) by a factor 2–3 in the $p_{\rm t}$ range from about 2 GeV/c to about 13 GeV/c, where the b-quark contribution dominates. When going to larger $p_{\rm t}$, the $R_{\rm CP}$ of muons increases fast and then flattens at around 0.8 at mid-rapidity and 1.0 at forward rapidity. This difference at high $p_{\rm t}$ between the two pseudo-rapidity regions is due to the different relative abundances of the heavy-quarks and weak bosons components. For the same reason, the curves for $\hat{q} = 25$ GeV^2/fm and 100 GeV^2/fm cross each other at $p_{\rm t} \approx 20$ GeV/c at large pseudo-rapidity and at $p_{\rm t} \approx 25$ GeV/c at mid-rapidity. We have checked that the uncertainties on the cross sections of muons from W decays and of muons from beauty decays (approximately 10% and 30%, respectively, as discussed in section 2) translate into a variation smaller than 5% of the $R_{\rm AA}$ and $R_{\rm CP}$ values for $p_{\rm t} \gtrsim 35$ GeV/c, while they have no effect at lower $p_{\rm t}$.

5 Conclusions

The effect of heavy-quark energy loss on the differential cross section of muons produced in Pb–Pb and pp collisions at LHC energies has been investigated. The most important contributions to the decay muon yield in the range 5 <

$p_t < 60$ GeV/c have been included: b (and c) quarks have been computed using a NLO pQCD calculation supplemented with the BDMPS mass-dependent quenching weights; weak gauge bosons muonic decays have been computed using the PYTHIA event generator. The heavy-quark mass-dependence of energy loss reduces the suppression of muon yields from beauty decays by about factor two for $5 \lesssim p_t \lesssim 15$ GeV/c. To account for the decrease of the medium density at large pseudo-rapidity, we assumed a decrease of the transport coefficient proportionally to $dN_{ch}/d\eta$, and we found that the effect on the muon p_t distribution is negligible, especially at large transverse momentum. We investigated the energy loss effect by means of the Pb–Pb-to-pp and of the Pb–Pb central-to-peripheral nuclear modification factors in the acceptance of the LHC experiments: ATLAS, ALICE, and CMS. In the p_t interval below approximately 20 GeV/c, where the beauty component is dominant, R_{AA} for 0–10% central Pb–Pb collisions relative to pp and R_{CP} for 0–10% relative to 40–70% Pb–Pb collisions are found to be about 0.2–0.4 and 0.3–0.5, respectively. Then, we observe a steep rise in the beauty/W crossover interval 20–40 GeV/c, up to the values $R_{AA} \approx 0.8$ and $R_{CP} \approx 1$ in the interval above 40 GeV/c, dominated by W/Z decay muons. These muon nuclear modification factors could provide the first experimental observation of the b quark medium-induced suppression in Pb–Pb collisions at the LHC. The presence of a medium-blind component (muons from W and Z decays) that dominates the high-p_t muon yield will allow an intrinsic calibration of the medium-sensitive probe (heavy quarks), because it will provide a handle on the strength of the initial-state effects that may alter the hard-scattering cross sections in nucleus–nucleus collisions at the unprecedented energies of the LHC.

Acknowledgments. The authors, members of the ALICE Collaboration, would like to thank their ALICE Colleagues for useful exchanges during the accomplishment of the present work. In particular, we would like to thank F. Antinori, P. Crochet, A. Morsch and J. Schukraft for fruitful discussions, N. Armesto and C. A. Salgado for their helpful suggestions at the beginning of this work and the calculation of the HKN parameterized nPDFs, and to S. Kumano and R. Sassot for the calculation of the HKN and the nDS parameterized nPDFs, and to M. Mangano for the HVQMNR program implementation.
This work is partly supported by the NSFC (10575044 and 10635020), the Key Project of the Chinese Ministry of Education (306022 and IRT0624) and the France China Particle Physics Laboratory, FCPPL (CNRS/IN2P3 and Chinese Ministry of Education).

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